NEXT-GENERATION MDAC DISCRIMINATION PROCEDURE USING MULTI-DIMENSIONAL SPECTRAL ANALYSES

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ABSTRACT

Theoretical understanding of regional P/S discriminants and their frequency dependence has been an important, long-standing research topic. Following Xie and Patton (1999), Fisk et al. (2005) and Fisk (2006) used modified Brune (1970) and Mueller and Murphy (1971) [MM71] models to explain the frequency dependence of Pn/Lg and Pn/Sn discrimination performance for earthquakes and underground nuclear explosions (UNEs) near the Lop Nor, Semipalatinsk, and Novaya Zemlya test sites as mainly due to differences in explosion P and S corner frequencies. Fisk (2007) used source model fits to estimate Pn, Pg, and Lg corner frequencies for Nevada Test Site (NTS) explosions and found that Lg corner frequencies exhibit similar scaling with source size as for Pn and Pg, but shifted lower, analogous to observations by Fisk (2006) for other test sites. A key result is that increasing separation of regional P/S at higher frequencies between earthquakes and explosions at all of these test sites has a consistent model-based explanation mainly in terms of the difference between explosion P and S corner frequencies. Discrimination begins to improve at the explosion S-wave corner frequency and saturates at the explosion P-wave corner frequency, in agreement with empirical experience obtained over decades. We describe how grids of P/S spectral ratios for all combinations of frequencies for P and S wave spectra, which exhibit far greater differences in relative spectral amplitudes and shapes between explosions and earthquakes than considered before, and source models can be used to significantly enhance discrimination performance and confirm the physical basis of the results. We have just started a three-year project to develop and test an innovative processing and discrimination procedure, based on robust features of multi-dimensional spectral ratios for regional seismic phases, and using comparisons to source models, that builds naturally upon the existing Magnitude and Distance Amplitude Correction (MDAC) technique (e.g., Taylor et al., 2002). Key aspects of this work will be to (1) compute two-dimensional (2D) spectral ratios for earthquakes and explosions at various nuclear test sites, using corrected spectra that will be available to us from an existing contract; (2) compare and correct empirical spectra using model predictions, based on a Brune earthquake model and new parametrizations of MM71 for explosion P and S waves; (3) assess features of the spectral ratios that capture spectral differences for various event types and enhance discrimination; (4) quantify uncertainties of the corrected spectral measurements for various regions, stations, and event types; (5) develop a discrimination procedure and test its performance on diverse sets of data, including applications to nuclear test sites and the Korean Peninsula; and (6) develop visualization techniques that allow the discrimination results and model comparisons to be assessed by a human analyst.

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OBJECTIVES

We have just started a project to develop and test an enhanced discrimination procedure, based on robust features of multi-dimensional spectral ratios for regional seismic phases, and utilizing source models. The objective is to develop a discrimination methodology and software tools that build upon the existing MDAC procedure by exploiting differences of relative spectral amplitudes and shapes due to source type that are currently not used, but are visually apparent (shown below). Another objective is to provide direct comparison of the empirical results to model calculations to confirm the physical basis of the discrimination results and, in turn, to better understand source mechanisms that affect regional discriminants. Below we motivate our approach and describe planned tasks.

Background and Motivation

Numerous independent empirical studies (Bennett et al., 1989; Taylor et al., 1989; Baumgardt et al., 1992; Kim et al., 1993, 1997; Walter et al., 1995; Fisk et al., 1996; Taylor, 1996; Taylor and Hartse, 1997; Hartse et al., 1997; and many others) have demonstrated that high-frequency (typically above 3-4 Hz) regional P/S ratios (e.g., Pn/Lg, Pn/Sn, Pg/Lg) provide useful separation of earthquakes and explosions. Fisk et al. (2001) provided a systematic comparison of regional waveforms and P/S ratios for explosions and earthquakes near all known nuclear test sites, which showed that regional P/S discriminants at frequencies above about 4 Hz provide useful discrimination in all site-by-site comparisons. (Note that valid application of P/S discriminants to broad areas requires treatment of significant variations due to distance, path, and station effects that must be properly calibrated on a region/station-specific basis.) While there is now a substantial body of empirical evidence that regional P/S ratios provide good discrimination at higher frequencies (e.g., above about 3–4 Hz) and poor discrimination at lower frequencies, we are just beginning to gain theoretical understanding of this phenomenon.

As observed by Xie and Patton (1999), frequency-dependent discrimination performance of Pn/Lg for earthquakes and explosions near the Lop Nor Test Site (LNTS) in China appears to be mainly due to differences in corner frequencies of P and S waves and spectral overshoot for explosions. Fisk et al. (2005) and Fisk (2006) confirmed this behavior of Pn/Sn and/or Pn/Lg spectral ratios for events near LNTS, STS, and NZTS. Figure 1 depicts locations of LNTS and STS nuclear explosions and earthquakes. Many STS UNEs up to 1989 were recorded digitally by BRV (Borovoye, Kazakhstan) and WMQ (Ulumuchi, China). More recent events, including LNTS explosions since mid 1994, were recorded digitally by up to 19 regional stations in Kazakhstan, Kyrgyzstan, Pakistan, Russia, Mongolia, and China.

Figure 2 shows Pn/Sn spectral ratios for nine LNTS nuclear explosions since 1992 with regional data (magenta curves), two explosions in 1996 (red curves), and two earthquakes in January 1999 (green curves). Preliminary attenuation and station corrections were applied to the individual phase spectra at the various stations; the Pn/Sn ratios were then formed and network averaged. Figure 2 also shows theoretical relative spectra predicted for the two 1999 earthquakes and the two 1996 nuclear explosions (gray and black curves, respectively), using a modified Brune (1970) model for earthquakes and an MM71 model for explosions in granite, including a conjecture by Fisk (2006) that the explosion S waves may be modeled by the same functional form as for P waves, but with corner frequency reduced by the ratio of near-source S and P velocities, $v_s(S)/v_s(P)$. The models adequately represent the empirical Pn/Sn spectral ratios and indicate that the frequency dependence of P/S discrimination performance is mainly due to different explosion P and S corner frequencies and stronger frequency-dependent spectral shapes (including overshoot) for explosions. Fisk (2006) used the same Brune and MM71 models at Lop Nor, Degelen, Balapan, and Novaya Zemlya, and showed similar results for Pn/Sn and/or Pn/Lg at all hard rock nuclear test sites. Namely, P/S discrimination emerges at the explosion S-wave corner frequency and saturates at the P-wave corner frequency. This result is in agreement with empirical experience obtained over several decades.

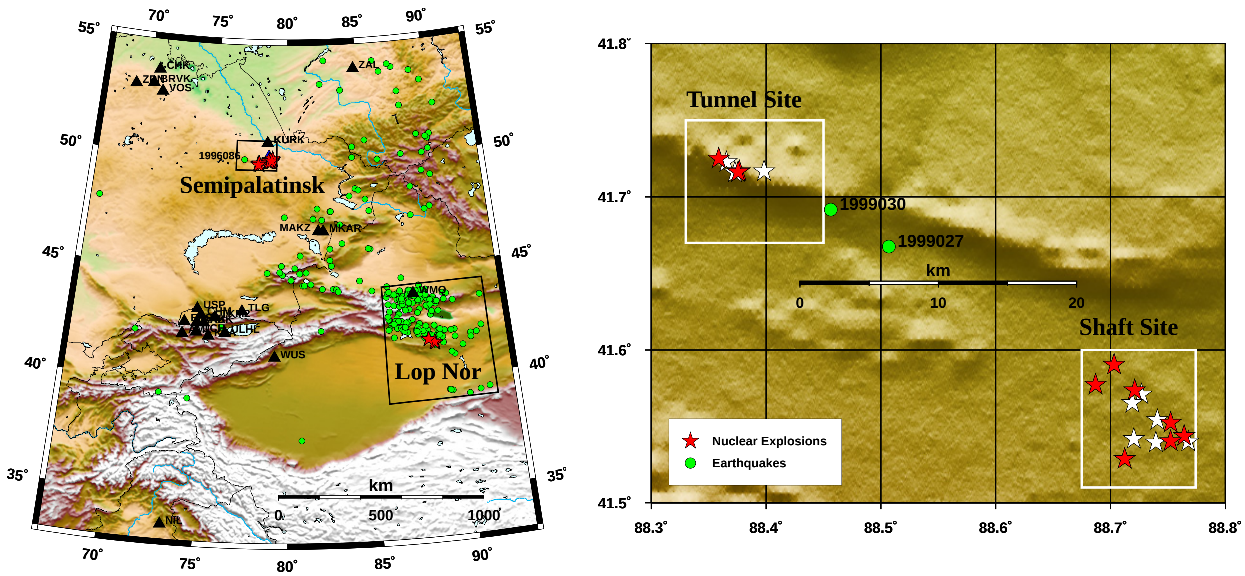

Figure 1. (Left) Locations of nuclear explosions and regional earthquakes considered by Fisk (2006). (Right) Enlarged view of LNTS, including 9 UNEs with regional data (red stars) and two nearby earthquakes in 1999.

Figure 2 not only illustrates a model-based explanation of why P/S discrimination performance is typically better at higher frequencies (i.e., above the Pn corner frequency for explosions, which depends on source size), but also that the earthquakes and explosions have fundamentally different spectral shapes, which should be exploited to improve discrimination. For example, the top and middle plots in Figure 3 shows the result of forming Pn/Sn spectral ratios for all combinations of frequencies for the Pn and Sn spectra of the 1999/01/27 (mb 4.0) and 1999/01/30 (mb 5.4) earthquakes and the 1996/07/29 (mb 4.7) and 1996/06/08 (mb 5.8) nuclear explosions. The spectra were limited to signal-to-noise ratio (SNR) greater than 2.5, which is why the grids for the smaller events have less extent. The spectral ratios for the events, which were corrected for attenuation and station effects, are now also all corrected by a modified Brune model, analogous to the MDAC approach (Taylor et al., 2002). (Alternatively, the spectral ratios could all be corrected by an explosion source model.) The 2D spectral plots for the earthquakes in Figure 3 have values close to zero and little variability over the usable bandwidth of Pn and Sn, as they should, if properly corrected for source, attenuation, and station terms. Alternatively, the plots for the explosions exhibit significant departures from zero and striking spectral structure, including spectral modulations due to overshoot and surface interference effects (Fisk et al., 2005). The bottom plots in Figure 3 show model predictions of the 2D spectral ratios for mb 4.7 and 5.8 explosions in granite. These grids were corrected by the same Brune model used for the empirical grids, so that a direct comparison may be made. It can be seen that these model results exhibit similar qualitative behavior as the corresponding empirical grids for the explosions (middle plots). Plots of Pn/Lg 2D spectral ratios for these events (not shown here) are very similar.

These 2D grids (convenient for plots) may be regarded as slices in a higher-dimensional discriminant space. The small squares in each plot of Figure 3 represent a typical frequency band used to measure P/S, which provides useful discrimination at LNTS, but is not optimal. Figure 3 indicates that cross-spectral ratios (e.g., Pn[3-8 Hz]/Sn[0.5 Hz]), advocated by Taylor et al. (2002), improve discrimination for LNTS events, now with a model-based interpretation. Also, multivariate methods that use combinations of P/S discriminants in high- and low-frequency (HF and LF) bands also tend to separate explosions and earthquakes better than just using the "best" single HF band because the correlations capture information regarding differences in spectral shapes between explosions and earthquakes;

however, not as effectively as could be done by characterizing the broader spectral structure shown in Figure 3.

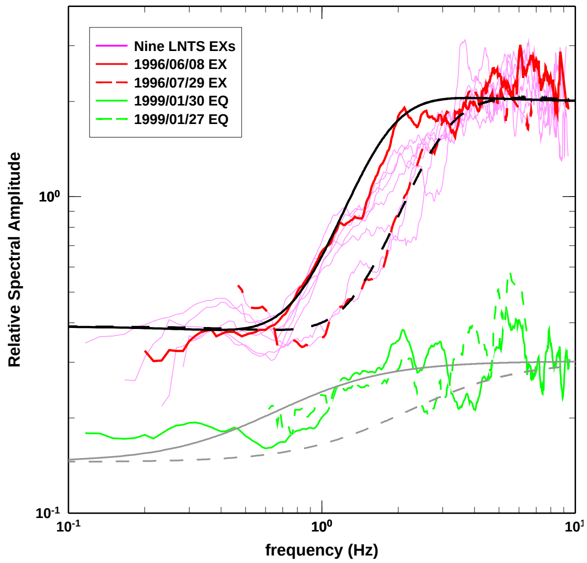

Figure 2. Network-averaged Pn/Sn spectral ratios, corrected for attenuation and station effects, for nine LNTS explosions and two nearby earthquakes. Model predictions are shown for two 1996 explosions and two 1999 earthquakes (black and gray curves).

Our objective is to improve regional discrimination by utilizing this much richer spectral content. Ultimately, we wish to compare features of empirical 2D spectral ratios to model calculations to provide confident event identifications with statistical and physical meaning. However, it is not necessary to match empirical 2D spectral ratios to explosion model calculations in order to successfully enhance regional discrimination. Just using the spectral content, as in the upper four plots of Figure 3, which do not utilize any explosion model information, can improve discrimination performance. This would be a natural extension of the MDAC procedure, using similar methods to correct amplitudes of regional phases for magnitude and distance effects, but then utilizing far more spectral information than currently used. Direct comparison to model predictions for explosions would be an added benefit.

Note that the empirical results for LNTS were averaged over 5 to 18 stations. In practical monitoring situations, events are typically recorded by only one or a few, at most, regional stations. Thus, path and station-specific variability is very important. The raw spectra of regional phases at various stations for LNTS events exhibit considerable variability, requiring different attenuation and station corrections. However, the qualitative frequency dependence of the network-averaged spectral ratios is also observed at the individual stations. As an example, the magenta curves in Figure 2 for nine UNEs, recorded by very different numbers (5 to 18) and subsets of stations, exhibit remarkable consistency in spectral behavior, after applying station-specific corrections. A necessary task will also be to quantify the variances associated with explosion and earthquake spectra over various stations, events, and source regions.

To illustrate applicability using only one station and to other test sites, Figure 4 shows Pn/Lg spectral ratios at WMQ, corrected for attenuation and station terms, for small and large UNEs (red curves) at Degelen and Balapan, and a nearby M_W 4 earthquake on 1996/03/26 using WMQ data only (cyan) and averaging over 17 stations (green). Fisk (2006) shows more results for 51 STS UNEs recorded by WMQ and/or BRV, and for NZTS UNEs. The gray curve in each plot is the Brune model prediction for the earthquake. The black curves are the MM71 model results for each explosion. The model and empirical Pn/Lg spectral ratios compare quite well, given that only one station is used for the UNEs. Figure 5 compares empirical (left) and model (right) Pn/Lg 2D spectral ratios for the earthquake (top), the 1988/09/14 JVE at Balapan (middle), and the 1987/07/17 UNE at Degelen (bottom). Despite the variability using only a single station, the model results exhibit similar behavior as the empirical grids for the UNEs.

As a final example, Figure 6 compares model and empirical 1D and 2D Pn/Sn spectral ratios for the 1998/05/11 UNE in India, using data from station NIL (Nilore, Pakistan). More work is needed to examine the behavior of P/S discriminants for other geological region types and more events, but a consistent model-based understanding of frequency-dependent P/S discrimination seems to be emerging, at least for all existing nuclear test sites on hard rock (Lop Nor, Balapan, Degelen, Novaya Zemlya, Indian).

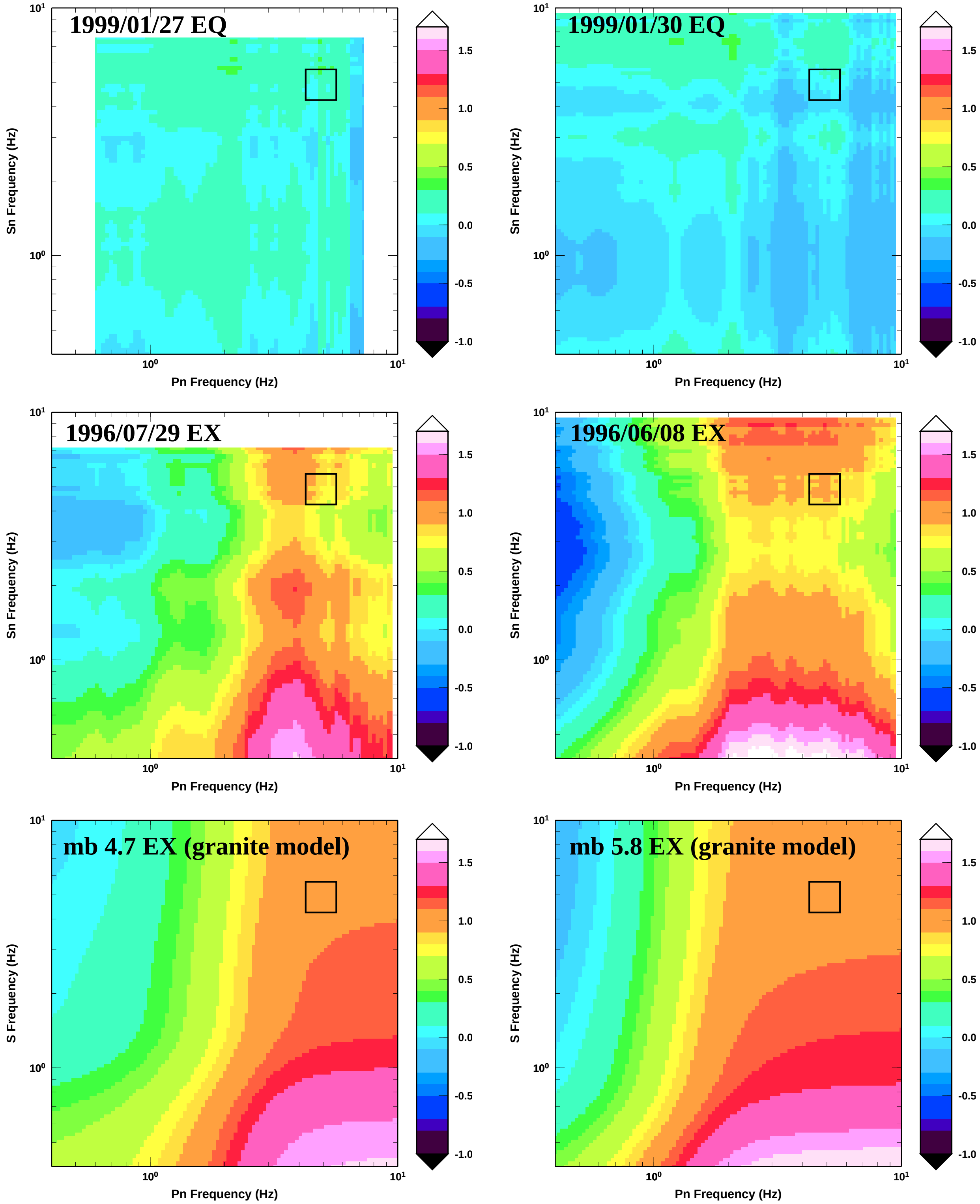

Figure 3. Contours of Pn/Sn 2D spectral ratios as functions of Pn and Sn frequencies for two earthquakes (top), two LNTS nuclear explosions (middle), and corresponding explosion model predictions (bottom). All spectra were corrected for attenuation and station effects, network averaged, and corrected for source size using a Brune model. The squares in each plot show typical frequency bands used to measure Pn/Sn.

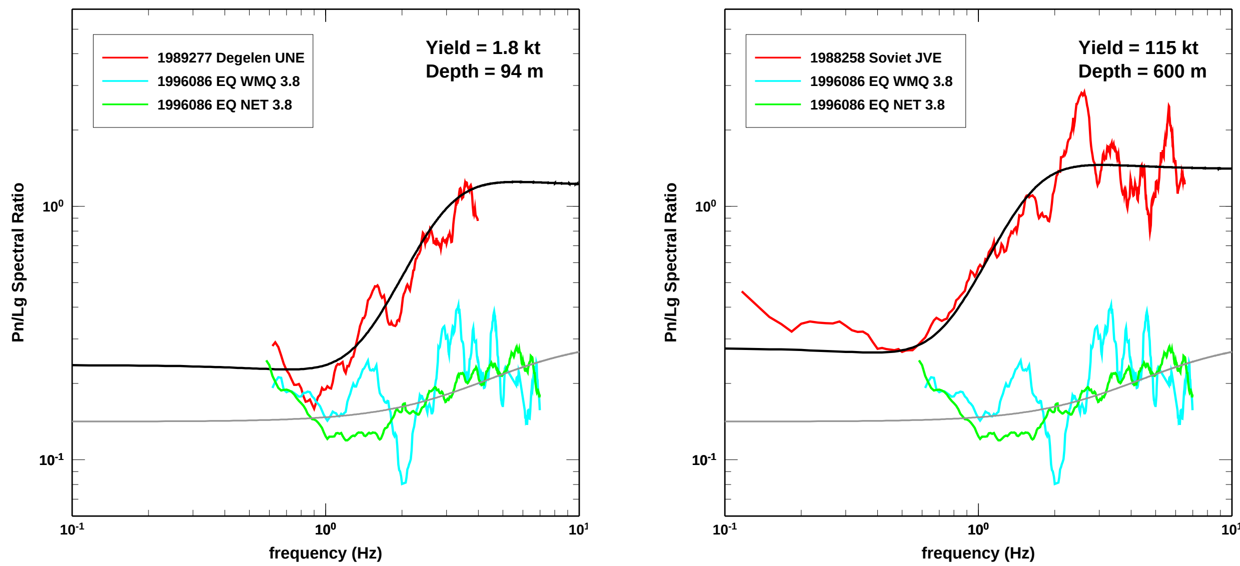

Figure 4. Examples of empirical and model Pn/Lg spectral ratios at WMQ for a Degelen explosion (left) and the 1988/09/14 Soviet JVE at Balapan (right). Pn/Lg spectral ratios, using WMQ only and network averaged over 17 regional stations, are shown for the nearby 1996/03/26 earthquake.

There are several caveats worth noting. First, theoretical understanding of explosion S waves is relatively limited at present. Although the MM71 source function, with S corner frequency scaling relative to the P corner frequency by $v_s(S)/v_s(P)$, provides reasonable interpretation of Pn/Sn and Pn/Lg ratios for explosions at hard rock (granite and shale) nuclear test sites (Fisk, 2006), further work is needed to model explosion S-waves in other types of media. In more recent work, Fisk (2007) processed regional seismograms for 68 NTS explosions above and below the water table in tuff, rhyolite, and alluvium and for 38 nearby earthquakes that were provided by Bill Walter of Lawrence Livermore National Laboratory (LLNL). Fisk (2007) corrected the spectra and computed model fits, using geological information of emplacement conditions from Springer et al. (2002). He found that Lg corner frequencies exhibit similar scaling with source size as for Pn and Pg, but shifted lower, analogous to observations by Fisk (2006) for other test sites. A key result is that increasing separation of regional P/S at higher frequencies between earthquakes and explosions at all of these test sites has a consistent model-based explanation mainly in terms of the difference between explosion P and S corner frequencies.

Existing work by other contractors, directed at quantifying explosion S wave models for diverse media and emplacement conditions, may also be directly applicable to our work. We expect that there will be considerable information compiled on explosion S-wave models for other types of media for this project and we reiterate that it is not necessary to model explosion S waves in order to successfully enhance regional discrimination capabilities.

Explosions in other types of media may not exhibit such dramatic spectral structure as in Figure 3. For example, MM71 predicts lower overshoot in tuff than granite, which would lead to different spectral behavior. Similar to the bottom two plots in Figure 3, Figure 7 shows model predictions for mb 4.7 and 5.8 explosions in tuff. In limited frequency bands (e.g., 4-6 Hz), the model results for tuff and granite are similar (cf. Figure 3), but the full spectral content provides more information regarding the differences in P/S explosion signatures due to different media properties. Despite some differences in spectral content for shots in tuff versus granite, both cases indicate very interesting spectral behavior that can be exploited to enhance regional discrimination.

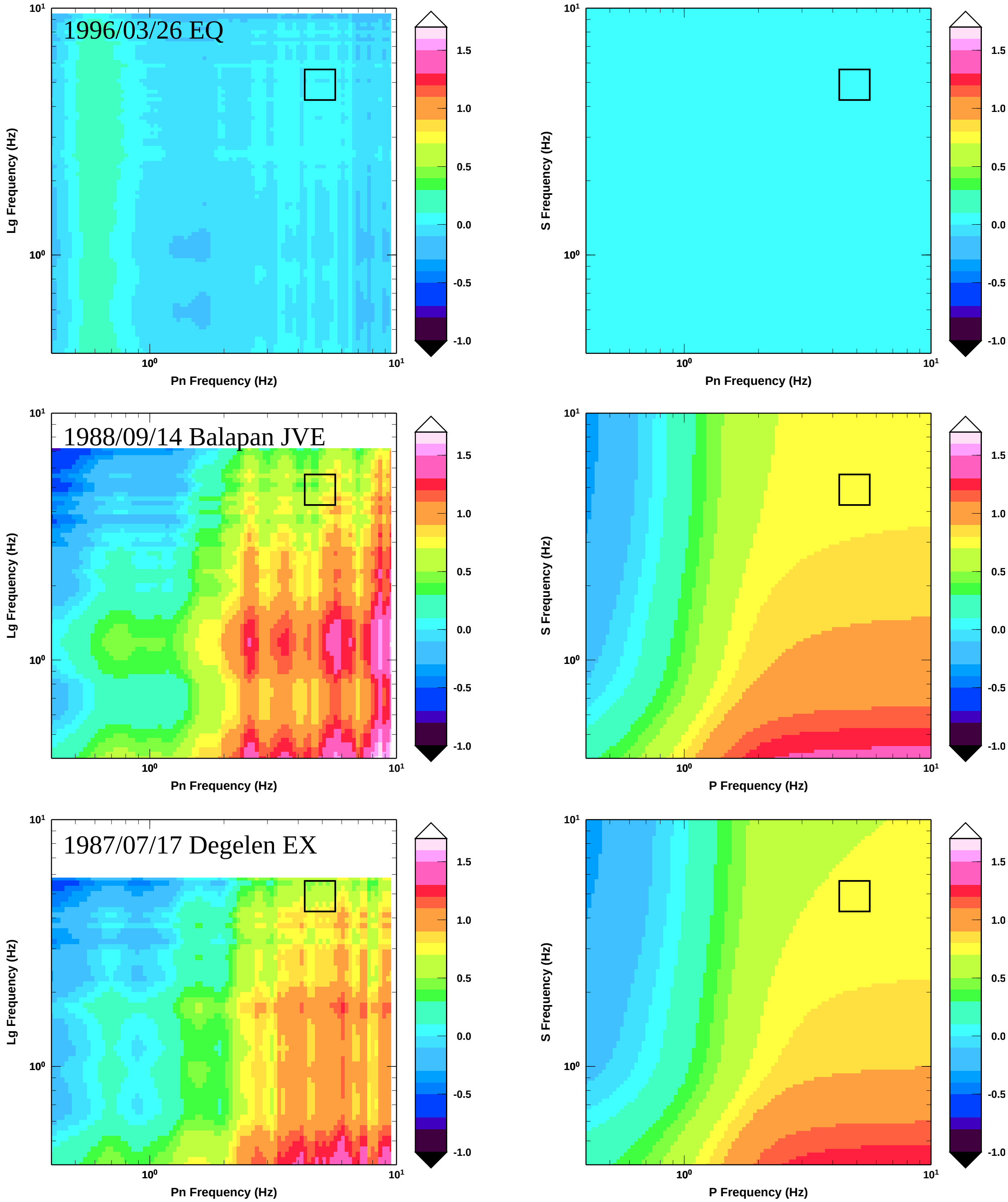

Figure 5. Comparison of empirical (left) and model (right) Pn/Lg 2D spectral ratios for the 1996/03/26 earthquake (top), the 1988/09/14 JVE at Balapan (middle), and the 1987/07/17 UNE at Degelen Mountain (bottom). The empirical grids for the explosions were computed using only a single station (WMQ).

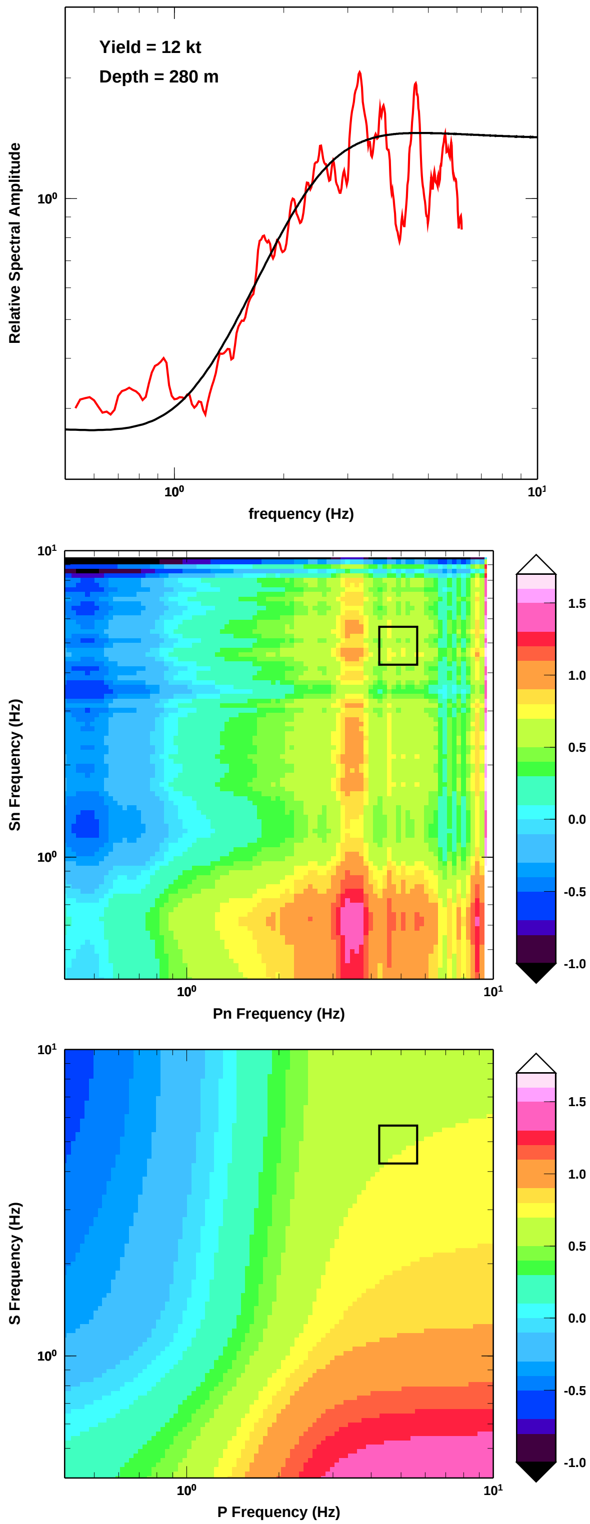

Figure 6. Comparison of model and empirical 1D (top) and 2D (lower two plots) Pn/Sn spectral ratios for the 1998/05/11 UNE in India, using data from station NIL (Nilore, Pakistan).

Second, a discrimination procedure should be developed and tested on a large, representative sets of explosions and earthquakes. Under past and existing contracts, we have assembled fairly comprehensive data sets of earthquakes and explosions near the Lop Nor, Novaya Zemlya, Semipalatinsk, Nevada, and Indian test sites. We have computed regional phase spectra and are correcting them for magnitude, distance, and station effects. Thus, most of the corrected spectra, necessary to develop and evaluate our proposed discrimination procedure, are available to us.

Third, SNR is expected to be lower for smaller events and for those at far regional distances. The effective bandwidth of 2D spectral ratios for many typical events will be more limited than some of the cases shown above. Blockage of regional phases and other strong attenuation effects must be considered and treated for any regional seismic discrimination approach. These issues will require robust procedures to handle the effective bandwidth of regional seismic phase spectra.

Although the focus of this effort is on P/S 2D spectral discriminants, we also plan to examine 2D spectral ratios for the same phase type. For example, use of Lg spectral ratios (Lg[HF]/Lg[LF]) has been an appealing idea for many years now (e.g., Murphy and Bennett, 1982; Taylor et al., 1988; Walter et al., 1995; Patton and Taylor, 1995) because Lg often has the highest SNR of regional phases and problems measuring weak Pn or Pg, or near their cross-over distance, are avoided. Whether information from Lg 2D spectral ratios can be used to improve discrimination on a consistent basis remains to be investigated. Even if the intrinsic discrimination performance, based on Lg 2D spectral ratios, is lower than for P/S, the overall monitoring performance may be enhanced significantly because of many more available Lg measurements for smaller events.

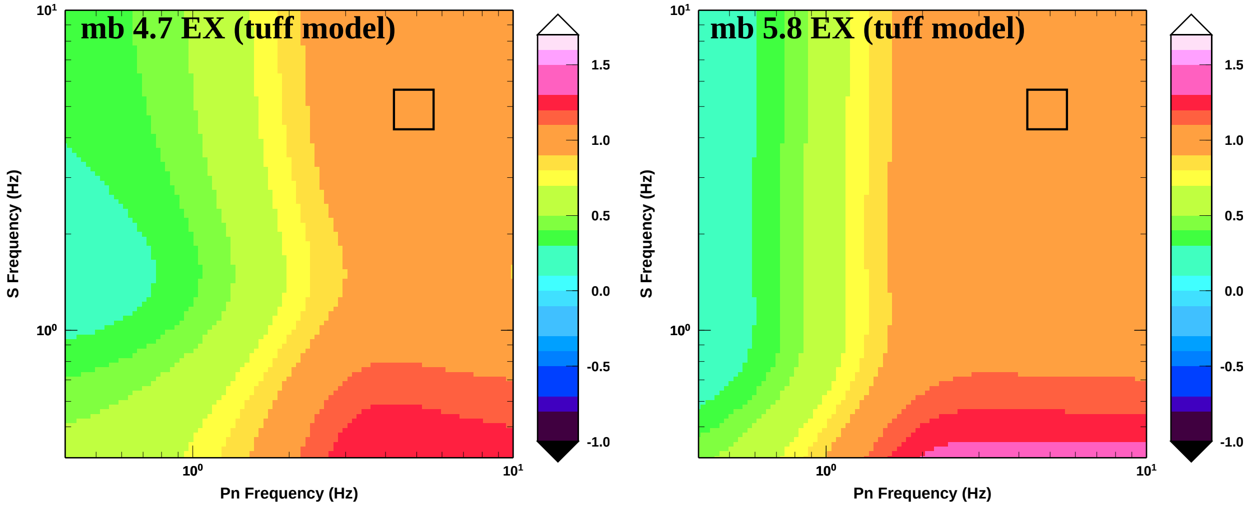

Figure 7. Model results for explosions in tuff, corrected by the same Brune model predictions as in Figure 3.

RESEARCH ACCOMPLISHED

Key tasks of this project will be to (1) compute 2D spectral ratios (Pn/Sn, Pn/Lg, Lg/Lg, etc.) for earthquakes and explosions at nuclear test sites, using corrected spectra that are available to us from past work; (2) compare and correct the empirical spectra using model predictions based on a modified Brune (1970) model for earthquakes and modifications of MM71 for explosion P and S waves, that are being compiled under an existing contract; (3) evaluate distinctive features of the 2D spectral ratios that robustly capture model-based spectral differences of various event types and enhance discrimination performance; (4) quantify uncertainties of the corrected spectra for various regions, stations, and event types, as well as misfits of empirical and model 2D spectral ratio comparisons; (5) develop a robust discrimination procedure and evaluate its performance on broad sets of data; and (6) develop visualization techniques that allow the discrimination results and model comparisons to be assessed by a human analyst. We will also tune and apply these techniques to events on the Korean Peninsula. The start date for this contract was too late to obtain results for this paper, but we are working on the first milestone of assembling and processing the data sets.

CONCLUSIONS AND RECOMMENDATIONS

We expect to develop enhanced processing and discrimination methods that provide significant improvements in seismic event discrimination performance using regional data. We believe that the planned efforts will lead to the next generation of regional discriminants and will provide LANL and LLNL with enhanced discrimination capabilities that could be incorporated straightforwardly into an existing event-identification framework. We further expect that the proposed methods, utilizing model-based comparisons and graphical display capabilities for earthquakes and explosions, will enhance the physical interpretation and visualization of the discrimination results and will, in turn, also provide better understanding of earthquake and explosion source processes that influence regional discriminants.

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